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14. ABSTRACT

The effort is primarily to accelerate delivery of an improved stability and transition analysis tool. The initial goal is to aid contractors supported under the DARPA FALCON program in the development and test of Common Aero Vehicle (CAV) maneuvering reentry configurations. Under this effort, state-of-the-art computational tools developed for hypersonic boundary layer stability research will be integrated into a user-friendly package (the Stability and Transition Analysis for Reentry tool, STAR). STAR will be based on Parabolized Stability Equation (PSE) solvers, with additional modules to account or crossflow, transient growth, and roughness effects. Previous flight and ground test data will be analyzed for validation and calibration of the new tool, and stability and transition on actual contractor-provided CAV configurations will be analyzed computationally in concert with ground tests of the same configurations.

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Stability and Transition Analysis for Reentry tool, STAR

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Stability and Transition Analysis for Reentry tool, STAR

Summary

The effort is primarily to accelerate delivery of an improved stability and transition analysis tool. The initial goal is to aid contractors supported under the DARPA FALCON program in the development and test of Common Aero Vehicle (CAV) maneuvering reentry configurations. Under this effort, state-of-the-art computational tools developed for hypersonic boundary layer stability research will be integrated into a user-friendly package (the Stability and Transition Analysis for Reentry tool, STAR). STAR will be based on Parabolized Stability Equation (PSE) solvers, with additional modules to account for crossflow, transient growth, and roughness effects. Previous flight and ground test data will be analyzed for validation and calibration of the new tool, and stability and transition on actual contractor-provided CAV configurations will be analyzed computationally in concert with ground tests of the same configurations.

The goal is to deliver source code and documentation that is to be made available at no charge to prospective users, as directed by the Department of Defense. The code will run on Linux clusters running MPI. Additional documentation will report the details of the test cases used for calibration and validation. STAR is to become a government-furnished code like POST, HYCOM, or CMA, which is available from a government source and continuously improved in terms of accuracy and range of applicability.

1. Technical Approach

Laminar-turbulent transition is critical to gliding hypersonic reentry vehicles and hypersonic airbreathing cruise vehicles, such as those presently being developed under the DARPA FALCON program. However, no ground-test facility can reliably evaluate transition, as none combine the low noise levels, high Mach numbers, high transition Reynolds numbers, and high enthalpy levels that are observed in flight. Reliable test and evaluation of transition-sensitive designs will require development of a new transition-prediction tool. This tool must extrapolate from new and existing ground experiments and existing flight data, to obtain reliable results for new designs in flight, without extensive flight testing. A reliable tool must be based on the actual physical mechanisms that lead to transition; such a tool now appears feasible due to continuing improvements in computational capabilities.

Therefore, the STAR program proposes to develop a mechanism-based transition prediction tool for hypersonic flows, to be first used for the gliding reentry vehicles associated with FALCON. This tool will be developed, calibrated, and validated using existing and new experimental data from ground and flight tests, both unclassified and classified. A comprehensive effort of this type has never been attempted before, as previous attempts to compare to flight data were carried out in the 1970's, when mechanism-based transition simulations were not feasible for flight vehicles.

The TEES/Texas A&M University team consists of Professor Helen Reed (U.S. citizen) and undergraduate/Masters student Richard Rhodes (U.S. citizen). Professor Graham Candler and Dr. Heath Johnson at the University of Minnesota are the developers of the prediction tool. Reed

and Rhodes are tasked with helping Candler and Heath formulate the extension to 3-D crossflow and general second-mode problems after the 2-D and linear problems are well in hand. Purdue is providing expertise in the physics and the experimental database, for both ground and flight tests, and will provide test cases. Schneider is also aiding in the interpretation of the experiments and the analysis of the computational results. In addition, Purdue is providing new experimental data in the Boeing/AFOSR Mach-6 Quiet Tunnel (presently running with conventional noise levels except at low pressures).

TEES/Texas A&M has advised and will continue to assist the Minnesota team in the development of mechanism-based transition-estimation modules based on the nonlinear parabolized stability equations (NPSE) for 3-D crossflow and general second-mode problems. Reed has visited Minnesota to discuss algorithms with plans to visit again as requested. The TEES/Texas A&M team has an independent NPSE capability in house in anticipation of helping verify the crossflow capability of the STAR program code once completed.

1.1 Transition Mechanisms in 2-D Boundary Layers

For high-speed flows, Reed et al. (1997) discuss progress on issues such as instability studies, nose-bluntness and angle-of-attack effects, and leading-edge-contamination problems from theoretical, computational, and experimental points of view. Also included is a review of wind-tunnel and flight data, including high-Re flight transition data, the levels of noise in flight and in wind tunnels, and how noise levels can affect parametric trends. When there is some knowledge of transition location, mean laminar and turbulent heat transfer can usually be computed to better than 25% accuracy. However laminar-turbulent transition in the boundary layer is usually estimated from crude algebraic correlations which usually do not contain physics. The scatter in these correlations can be a factor of 2 or more. For example, because transition causes heat transfer to rise by a factor of about 5 in high-speed flows, this uncertainty in transition location dominates overall uncertainty in heat-transfer predictions. Clearly, knowledge of the transition process is crucial for accurate vehicle heating and drag predictions over the whole flight regime.

Considerable uncertainty exists in both the prediction and control of transition in high-speed flows due to the dearth of reliable experiments. Here we concentrate on the basic fundamental differences between subsonic and supersonic streamwise instabilities in order for the reader to better understand transition control and prediction methods. The paper by Mack (1984) is the most complete description of compressible stability available anywhere.

The effect of compressibility in the high subsonic/low supersonic range is normally stabilizing, but at higher Mach numbers the nature of the instabilities changes. Linear stability theory is generally acknowledged to capture the physics of streamwise instabilities, and uncovers three major differences between high-speed boundary-layer analysis and subsonic analysis: the presence of a generalized inflection-point, multiple acoustic modes (Mack Modes), and the dominance of 3-D viscous disturbances.

The lowest-frequency Mack mode, the so-called second mode, is found to be the dominant instability for Mach number greater than about 4; it is more unstable than either the 3-D first mode or any of the other higher modes. With regard to the second mode, there is a strong tuning

with the boundary-layer thickness, so that the frequency of the most amplified disturbance may be predicted from this flow parameter. In particular, the fluctuation wavelength is approximately twice the boundary-layer thickness. This implies that if the boundary-layer thickness is changed, for example by cooling, a corresponding, predictable change in frequency should be observed. Mack observed that whereas the first mode is stabilized by cooling in air, the second mode is actually destabilized. The Mack modes can be destabilized without the presence of a generalized inflection point.

Linear stability solutions for hypersonic flows are complicated for some of the following reasons. 1) At hypersonic speeds, the gas often cannot be modeled as perfect because the molecular species begin to dissociate due to aerodynamic heating. In fact, sometimes there are not enough intermolecular collisions to support local chemical equilibrium and a nonequilibrium-chemistry model must be used. 2) The bow shock is close to the edge of the boundary layer and must be included in studies of transition. One has to account for a curved shock and the entropy layer. 3) Surface ablation can be a very significant effect. 4) The flow is highly 3-D in the neighborhood of drag flaps or fins, or when at angle of attack.

Malik (1987, 1989, 1990) investigated the stability of an equilibrium-air boundary layer on an adiabatic flat plate. Malik et al. (1990) used the eN method for the reentry-F experiments; the basic state was calculated by equilibrium-gas Navier-Stokes and PNS. Gasperas (1990) studied stability for an imperfect gas. Stuckert & Reed (1994) analyzed the stability of a shock layer in chemical nonequilibrium and compared results with the flow assuming 1) local chemical equilibrium and 2) a perfect gas.

Stuckert & Reed's coordinate system for both the basic-state and stability analysis fit the body and bow shock as coordinate lines. This makes it easier to apply the linearized shock-jump conditions as the disturbance boundary conditions. At the surface of the cone, for the nonequilibrium calculations, the species mass fluxes were set to zero (noncatalytic wall), whereas for the equilibrium calculations the disturbances were assumed to be in chemical equilibrium. It is clear that the equilibrium and nonequilibrium solutions can differ significantly depending on the rates of the reactions relative to the time scales of convection and diffusion. For example, some of the equilibrium modes were determined to be supersonic modes, each of which was a superposition of incoming and outgoing amplified solutions in the inviscid region of the shock layer. (No similar solutions were found for the nonequilibrium shock layer.) The magnitudes of these modes oscillated with y in the inviscid region of the shock layer. This behavior is possible only because the shock layer has a finite thickness. They are also unlike Mack's higher modes (except for the second) in that the disturbance-pressure phase for all of these supersonic modes changed most across the inviscid region of the shock layer. (The disturbance-pressure phase change for Mack's higher modes occurs across the viscous region of the flow, i.e. the boundary layer.) In fact, the disturbance-pressure phase change for all of these supersonic modes through the boundary layer is comparable to that of Mack's second mode.

Another effect of the chemical reactions is to increase the size of the region of relative supersonic flow primarily by reducing the temperature in the boundary layer through endothermic reactions, increasing the density, and hence decreasing the speed of sound. This reduces the frequency of the higher modes; in particular, the most unstable one, the second

mode. The higher modes in the reacting-gas cases are also more unstable relative to the corresponding perfect-gas modes. The first modes are, however, more stable.

Finally, the finite thickness of the shock layer has a significant effect on the first-mode solutions of all of the families. The effect on higher-mode, higher-frequency solutions does not seem to be as large as long as they are subsonic. This is perhaps what one would intuitively expect because the shock is likely "stiff" and hence difficult to perturb with smaller-wavelength, larger-wavenumber, higher-frequency disturbances. However, the nonparallel effects are known to be large for first-mode solutions, and so a complete quantitative description of the effects of the finite shock-layer thickness needs either a PSE solution or a DNS analysis.

The inclusion of the bow shock is especially critical to studies of leading-edge receptivity as demonstrated by Zhong (1997). His DNS results over a blunt wedge show that the instability waves developed behind the bow shock consist of both first and second modes. His results also indicate that external disturbances, especially entropy and vorticity disturbances, enter the boundary layer to generate instability waves mainly in the leading-edge region.

Validation. LST has been validated recently for 2-D high-speed flow (Lyttle, Reed, et al. 2005) and is currently the method of choice in modeling streamwise instabilities.

As Schneider (2001) points out, accurate depiction of the growth of a second-mode instability wave over a circular cone at zero-angle of attack remains a challenge, both computationally and experimentally. The series of experiments performed by Stetson et al. (1984), who consider the growth of instabilities on right-circular cones (both sharp and blunted) at zero-angle-of- attack at Mach 8, serves as a benchmark for subsequent computations. Numerical comparisons to the observed growth of second-mode instabilities over the spherically blunted-cone are reported by Malik et al. (1990), Esfahanian (1991), Kufner et al. (1993), and Rosenbloom et al. (1999). Agreement with the experimentally observed growth rates can be described as qualitative.

The Stetson et al. (1984) geometry is a 7° half-angle right-circular cone, with a blunted nose of radius 3.81 mm. The total length of the model is just over 1 m ($s = 267$). The free-stream flow is Mach 8, with zero-incidence with respect to the cone's axis. The Reynolds number (based upon free-stream conditions and the nose radius) is 3.3×10^5. The focus of the experiment is the second-mode instability, which is thought to be dominant for high-speed flows over smooth, convex, axi-symmetric geometries in two-dimensional flow.

Schneider (2001) summarizes the Stetson experimental conditions very efficiently. Paraphrasing Schneider, the total pressure is 4.00 MPa; the total temperature is 750 K. On the cone, surface measurements are taken for pressure and temperature. Basic-state profiles are measured using total-temperature and pitot-pressure probes. Basic-state comparisons between experimentally determined profiles and computed profiles are discussed below. For the Stetson experiment, disturbances are measured using a series of four hot-wire anemometers. Starting at 0.254 m (s = 66:7), disturbance spectra are measured through 0.922 m (s = 242). The measured total-temperature spectra are shown in Figure 5; it bears repeating that $\omega = 1$ corresponds to $f^* = 49.5$ kHz. The second-mode disturbances correspond to the spectral peaks that appear in the range $2.5 < \omega < 3$.

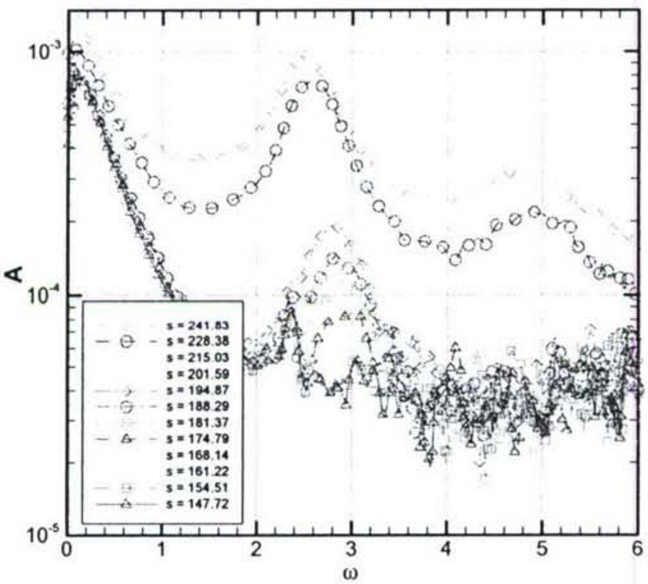

Figure 1: Stetson experiment: measured disturbance spectra of total temperature

From Figure 1, there follow some observations about the experiment. Firstly, Schneider (2001) notes that the experimental (free-stream) environment is not quiet, thus Figure 1 shows the growth of broadband, uncontrolled disturbances that result from the free-stream noise. Secondly, one notices the presence of a harmonic of the second-mode disturbance, starting at s = 215. This implies that non-linear interactions may be important downstream of s = 215. Summing up, the validity of comparing these experimental results with linear stability theory is limited by the free-stream disturbance environment and the possible presence of non-linear interactions.

Following Malik et al. (1990), many numerical investigators have chosen s = 175 as the place to make a comparison with the second-mode growth-rates reported by Stetson. As seen in Figure 2, the numerically determined growth rates (including Lyttle et al. 2005) consistently peak roughly 60% higher than the peak growth-rate reported by Stetson. There have been a variety of theories to try to explain this discrepancy. Schneider (2001) points out that Stetson postulates that non-linearities are present at station 175, visible in Figure 7b in Stetson et al. (1984). It has been pointed-out that the wall temperature at $s = 175$ is not adiabatic, whereas the numerical (basic-state) models assume an adiabatic wall. Mack (1987) points out that the origin of the disturbances (receptivity) is not addressed by linear-stability theory - nor by the experiment. Furthermore, Mack (1987) points out that the experimentally determined growth rates are found using the y-locations that have the peak wide-band response - not with regard to the location of the peak of an individual frequency component. New experimental initiatives, led by Schneider et al. (2002) and Maslov (2001), address these issues.

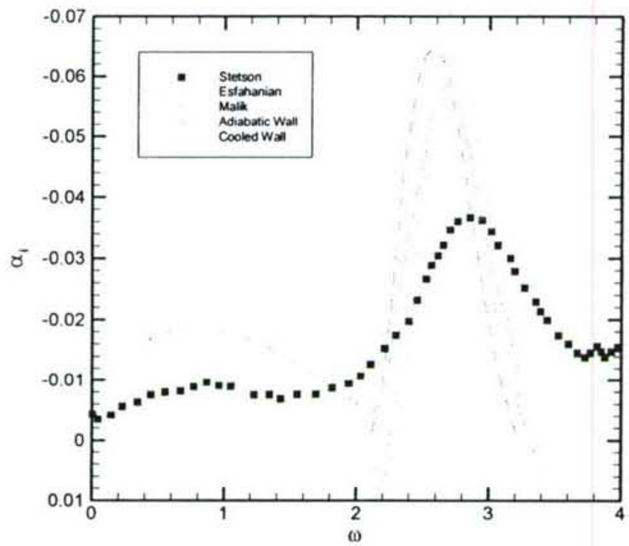

Figure 2: Second-mode growth rates as functions of frequency at s=175.

Using a finite-volume code developed in-house, Lyttle et al. (2005) solve the Navier-Stokes equations for these conditions and use the solutions to perform linear-stability analyses to determine the growth of second-mode disturbances. The traditional approach for numerically investigating the Stetson et al. (1984) case is to model the cone-wall as being adiabatic. This is the standard boundary-condition used by numerical investigators, and was the intent of the Stetson experiment. As Schneider (2001) points out, this assumption is not supported by the experimental evidence. The computed adiabatic wall temperature distribution is higher than the experimentally measured temperature distributions. Schneider further observes that, as consecutive experimental runs are made, the measured temperature distribution rises from run to run, until an equilibrium temperature distribution is reached. Schneider hypothesizes that the heat capacity of the model prevents the wall temperature from reaching the adiabatic value. Lyttle et al. (2005) incorporate an option to use an experimentally determined wall-temperature distribution for the basic state.

Following the suggestion of Schneider (2001), comparisons are made of integrated growth-rates among the computations and the experiments. This may be a more appropriate comparison because the experiments measure the disturbance amplitudes, then calculate the growth-rates based on the change in disturbance amplitudes. The integrated growth-rates, N-factors, depend on the two integration-endpoints s_0 and s_1, and are calculated as follows:

$$N = \ln\left(\frac{A_1}{A_0}\right) = \int_{s_0}^{s_1} -\alpha_i \, ds \qquad (1)$$

To place the current results in the context of the Stetson experiment, the adiabatic-wall, cooled-wall, and Stetson N-factors are compared, using $s = 195$ as the reference location. The current

results' agreement with the experimental results is best in the range of frequencies $2.4 < \omega < 2.8$. Examining the experimentally determined amplitudes from Figure 1, this frequency range corresponds with those frequencies that are most-amplified in the experiment.

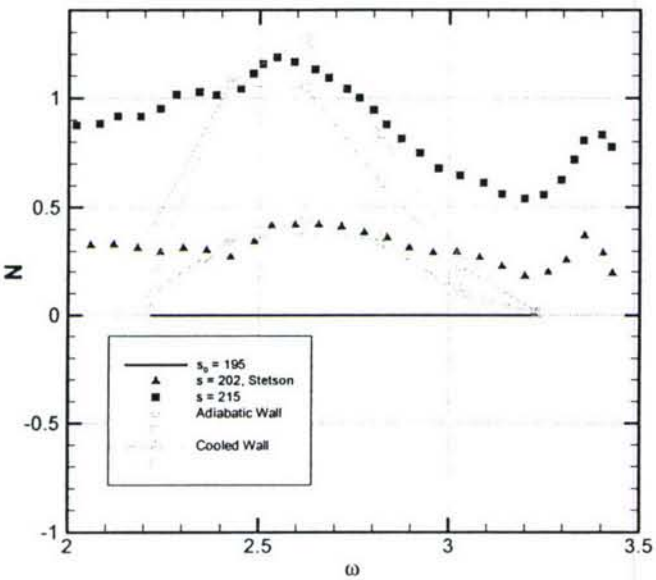

Figure 3: Comparison of N-factors, s_0=195, Stetson case (Lyttle et al. 2005).

The N-factor curves for a series of individual disturbance waves are considered, using s = 195 as the reference location. It is surmised that if a discernible linear-growth region exists, the extent of such a region can be identified by choosing $s_0 = 195$. For example, the results for $\omega = 2.62$ are shown in Figure 4, demonstrating the existence of a linear-growth region. The traditional under-prediction of growth-rates at s = 175 might also be explained by examining Figure 4.

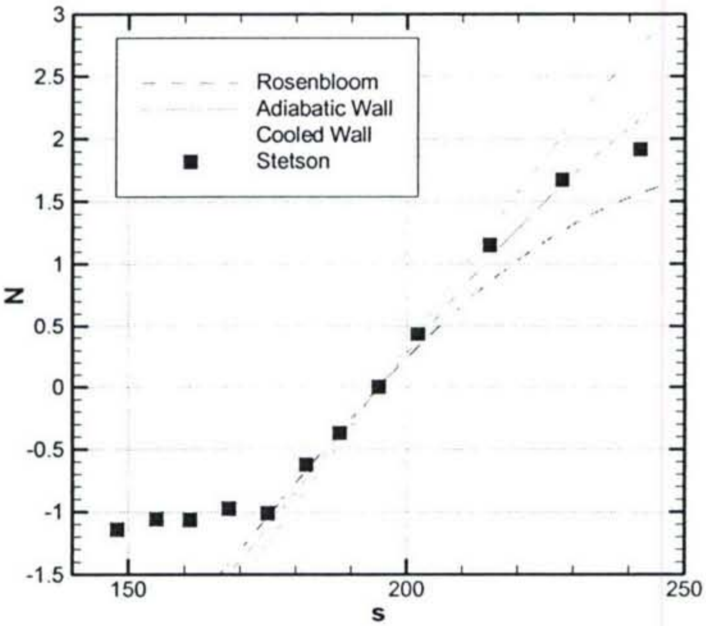

Figure 4: N-factor comparison, ω=2.62, Stetson case (Lyttle et al. 2005).

In conclusion, Lyttle et al. (2005) propose that linear-stability theory describes the growth of second-mode disturbances for $2.4 < \omega < 2.8$, and for the region $195 < s < 215$. The frequencies in this range correspond to the most-amplified second-mode frequencies. Upstream of $s = 195$, it is postulated that the amplified second-mode waves have not yet fully distinguished themselves from the noise. Indeed, the experimental N-factor curves suggest that the experimental-numerical disjoint at $s = 175$ may be attributed to signal-noise problems, rather than to non-linearity. For locations downstream of $s = 215$, perhaps non-linear interactions are important – behavior that cannot be captured using LST. Also, the agreement between the experiment and the current predictions appears better for the computations that use an experimentally determined wall-temperature distribution. Similar successful second-mode validation was done with the Mach 6 spherically blunted cone experiments in the T-326 hypersonic blow-down wind tunnel at the Institute of Theoretical and Applied Mechanics in Russia- see Figure 5.

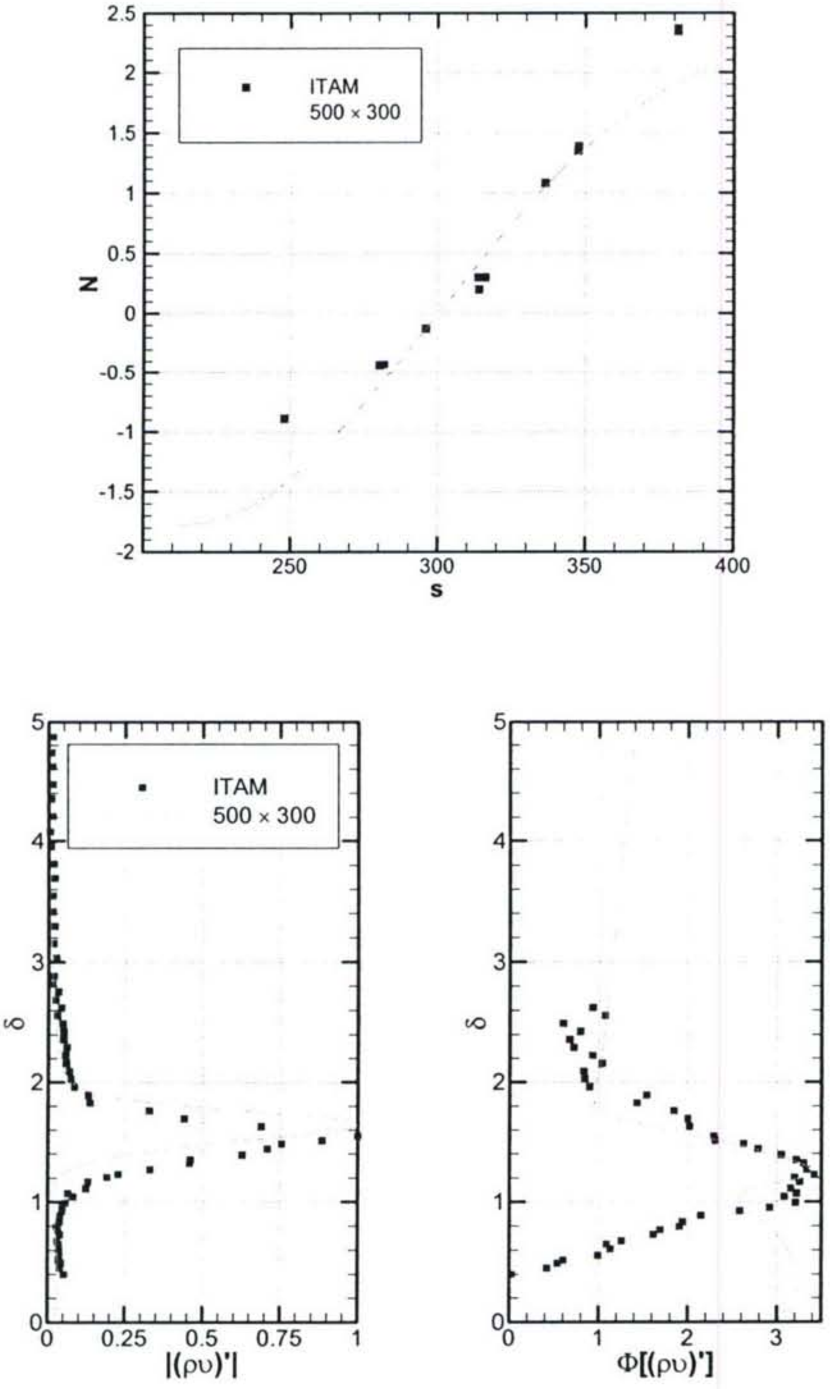

Figure 5: Second-mode comparisons with ITAM experiments (Lyttle et al. 2005).

1.2 Transition Mechanisms in 3-D Boundary Layers

Transition to turbulence in crossflow-dominated, swept-wing boundary layers has received considerable attention over the past decade or so. The reason is the obvious engineering benefit that would result from enabling laminar flow over most of the wing. The difficulty faced in confronting this problem has been the strongly nonlinear nature of the crossflow instability. Linear methods have been unable to completely predict absolute transition location and therefore tremendous effort has been given to understanding the nonlinear aspects of the phenomenon. The basic review of swept wing stability was given by Reed and Saric (1989) while recent reviews of crossflow efforts have been given by Arnal (1997), Bippes (1997, 1999), Crouch (1997), Haynes and Reed (2000), Herbert (1997), Kachanov (1996), Reibert and Saric (1997), Reshotko (1997), and Saric et al. (1998, 2003).

The papers of Reed and Saric (1989), Kohama et al. (1991), Kachanov (1996), Arnal (1997), Bippes (1997), and Saric et al. (2003) provide an extensive list of references for the recent experiments, including the DLR experiments in Germany on a swept flat plate, a Russian swept-flat-plate experiment, the CERT/ONERA experiments on swept wings, the Institute of Fluid Science work in Sendai on cones and spheres, and the Arizona State University (ASU) swept-wing experiments. These papers established the existence of both traveling and stationary crossflow vortices, saturation of the stationary crossflow vortex, the nonlinear secondary instability leading to transition, and the sensitivity to freestream disturbances and surface roughness. Here are some great challenges to the computationalist.

One of the key missing ingredients in all 3-D boundary layer experiments is the understanding of receptivity. Receptivity has many different paths through which to introduce a disturbance into the boundary layer and this "road map" is more complicated because of the amplified stationary vortices. In fact, many aspects of transition in 3-D boundary layers are orthogonal to 2-D boundary layers so such a "road map" is either not unique or too complicated. Aside from the usual mechanisms, such as the interaction of freestream turbulence and acoustical disturbances with model vibrations, leading-edge curvature, attachment-line contamination, discontinuities in surface curvature, etc., the presence of roughness that may enhance a stationary streamwise vortex is very important. In contrast to 2-D boundary layers where small 2-D roughness is important and 3-D roughness is less important unless it is large, the 3-D boundary layer appears to be very sensitive to micron-sized 3-D roughness. In this case, 2-D roughness is only important at its edges.

The net result of the previous efforts is a very complete understanding of the primary crossflow instability, including details of the nonlinear saturation of the dominant stationary mode and the growth of harmonics. An important consequence is that a means of transition suppression has been developed by Saric et al. (1998) that exploits the nature of the nonlinearities.

1.3 Transition Predictions in 3-D Boundary Layers

For 3-D boundary layers (e.g. swept wings) and also Görtler problems (concave surfaces; Saric 1994), nonlinear distortions of the basic flow may occur early on due to the action of the *stationary* primary instability. These flows are characterized by an extensive distance of

nonlinear evolution with eventual saturation of the fundamental disturbance, leading to the strong amplification of very-high-frequency inflectional instabilities and breakdown. Here linear stability theory (LST) is not successful (Reed et al. 1998). However, the NPSE, which have significantly less resource overhead associated with them compared with direct numerical simulations (DNS), have been shown to accurately model transition in a variety of relevant flows when the environment and operating conditions are modeled correctly.

Computationalists Haynes & Reed (2000) and experimentalists Reibert et al. (1996) together systematically studied basic mechanisms and sorted out the effects of curvature, roughness, and nonlinearities in incompressible 3-D boundary layers, and elucidated a very promising strategy for laminar flow control. This team developed and validated the NPSE with experiments on an NLF(2)-0415 swept airfoil. As a baseline case to study the evolution of crossflow vortices, roughness elements with a spanwise spacing of 12 mm were placed on the experimental model. Figure 6 shows a comparison of the experimental and computational total streamwise velocity contours at 45% chord; the agreement between the NPSE and the experiments is excellent. Figure 7 shows the comparison of the experimental -factor curves with various linear theories and NPSE. It is clear that the linear theories fail to accurately describe the transitional flow for this situation and that the NPSE does an excellent job of capturing the details for very little computational expense. This work then led to the novel idea of applying subcritically spaced, micron-sized roughness near the leading edge to maintain laminar flow on a swept wing (Saric et al. 1998), and then to supersonic 3-D boundary layers (Saric & Reed 2002).

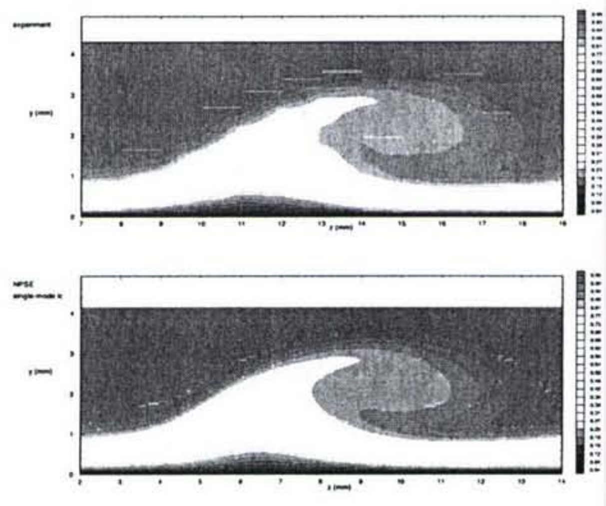

Figure 6: Streamwise-velocity contours for NLF(2)-0415 45° - sweep, $R_c = 2.4 million, \lambda_z = 12mm$, 45% chord. Excellent agreement between NPSE with curvature and experiments.

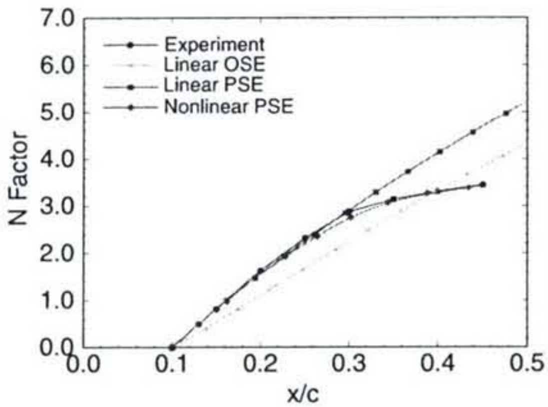

Figure 7: N factors for NLF(2)-0415 45° - swept airfoil, $R_c = 2.4 million, \lambda_z = 12 mm$. Shown is the excellent agreement between NPSE with curvature and the experiments.

An interesting feature of the stationary crossflow waves is the destabilization of secondary instabilities. The u' distortions created by the stationary wave are time-independent, resulting in a spanwise modulation of the mean streamwise velocity profile. As the distortions grow, the boundary layer develops an alternating pattern of accelerated, decelerated, and doubly inflected profiles. The inflected profiles are inviscidly unstable and, as such, are subject to a high-frequency secondary instability (Kohama et al 1991; Malik et al 1994). This secondary instability is highly amplified and leads to rapid local breakdown. Because transition develops locally, the transition front is nonuniform in span and characterized by a "saw-tooth" pattern of turbulent wedges.

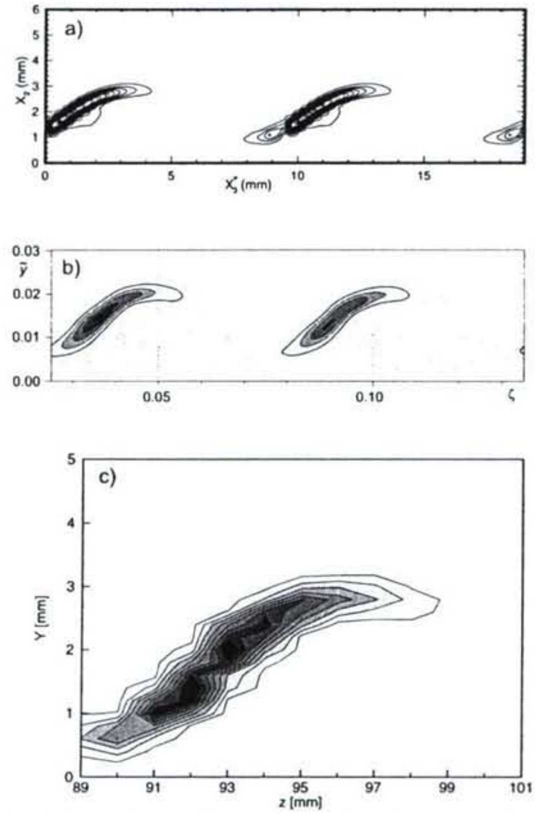

Figure 8: Mode-I velocity fluctuation contours (a) Figure 7 from Malik et al. (1999), (b) Figure 20b from Wassermann & Kloker (2002), and (c) Figure 11 from White & Saric (2002).

At this time, the various approaches to the secondary instability problem, experimental, nonlinear PSE, and DNS, have achieved rather remarkable agreement in terms of identifying the basic mechanisms of the secondary instability, unstable frequencies, mode shapes, and growth rates. The comparison shown in Figure 8 shows excellent agreement on the location of the breakdown and that it is associated with an inflection point in the spanwise direction (an extremum in $\partial U/\partial z$).

2. NPSE Formulation

In recent years PSE has become a popular approach to stability analysis owing to their inclusion of nonparallel and nonlinear effects with relatively small additional resource requirements as compared with DNS. The Texas A&M team now has an in-house capability in PSE.

For linear PSE (LPSE), a single monochromatic wave is considered as the disturbance, which is decomposed into a rapidly varying "wave function" and a slowly varying "shape function". Using a multiple-scales approach

$$\phi'(x, y, z, t) = \underbrace{\bar{\phi}\,(x/R, y)}_{\text{shapefunction}} \;\; \underbrace{\chi\,(x, z, t)}_{\text{wavefunction}} + c.c. \tag{2}$$

where

$$\partial\chi/\partial x = i\,\alpha(x/R)\,\chi,\ \ \partial\chi/\partial z = i\,\beta\,\chi,\ \ \partial\chi/\partial t = -i\,\omega\,\chi \tag{3}$$

The "shape function" $\bar{\phi}$ and streamwise wavenumber α depend on the slowly varying scale $\bar{x} = x/R$ while the "wave function" χ depends on the rapidly varying scale x. The frequency is ω and the spanwise wavenumber is β. This gives the following form for the streamwise derivatives of disturbance quantities

$$\begin{aligned}
\frac{\partial\phi'}{\partial x} &= \left\{\frac{1}{R}\frac{\partial\bar{\phi}}{\partial\bar{x}} + i\alpha\bar{\phi}\right\}\chi + c.c. \\
\frac{\partial^2\phi'}{\partial x^2} &= \left\{\frac{1}{R^2}\frac{\partial^2\bar{\phi}}{\partial\bar{x}^2} + \frac{2i\alpha}{R}\frac{\partial\bar{\phi}}{\partial\bar{x}} + \frac{i\bar{\phi}}{R}\frac{d\alpha}{d\bar{x}} - \alpha^2\bar{\phi}\right\}\chi + c.c.
\end{aligned} \tag{4}$$

The explicit streamwise $O\left(\frac{1}{R^2}\right)$ second-derivative term is neglected. This yields the following system of equations

$$\left(L_0 + L_1\right)\bar{\phi} + L_2\frac{\partial\bar{\phi}}{\partial\bar{x}} + \bar{\phi}L_3\frac{d\alpha}{d\bar{x}} = 0 \tag{5}$$

Here L_0 is the Orr-Sommerfeld operator, L_1 contains the nonparallel basic-state terms, and L_2 and L_3 arise due to the nonparallel disturbance terms.

The resulting system of equations is parabolic, so to complete the formulation, upstream (initial) and boundary conditions must be specified. The disturbance quantities are zero at the wall and as $y \to \infty$. If the analysis begins in a region where the initial disturbance amplitudes are small, linear stability theory can be used to obtain these initial conditions.

There still remains the matter of the ambiguity in streamwise dependence; applying a normalization condition ensures that any rapid changes in the streamwise direction will be "absorbed" by the wave function so that the shape function will vary slowly in this direction. For example, Haynes & Reed (2000) suggest the integral normalization

$$\rho = \int_0^\infty \bar{u}^t \frac{\partial\bar{u}}{\partial\bar{x}}\,dy = 0 \tag{6}$$

Assuming the solution is known at streamwise location x^i, Haynes & Reed (2000) suggest the following streamwise marching algorithm:

1. Guess $\alpha\left(x^{i+1}\right)$
2. Solve equation 1 for ϕ^{i+1}

3. Use ϕ^{i+1} to compute the error ρ
4. Use Newton's method with ϕ^{i+1} to update $\alpha\left(x^{i+1}\right)$
5. Repeat steps 2-4 until ρ is less than some tolerance.

The nonlinear PSE (NPSE) are derived in a fashion similar to LPSE with the exception that each disturbance quantity is transformed spectrally in the spanwise and temporal directions

$$\phi'(x, y, z, t) = \Sigma^{\infty}_{n=-\infty} \Sigma^{\infty}_{k=-\infty} \underbrace{\bar{\phi}_{(n,k)}(x/R, y)}_{\text{shapefunction}} \underbrace{A_{(n,k)}\, e^{i(k\beta_0 z - n\omega_0 t)}}_{\text{wavefunction}} \tag{7}$$

where

$$\frac{dA_{(n,k)}}{dx} = A_{(n,k)} i\alpha_{(n,k)}(\bar{x}) \tag{8}$$

Here each mode (n,k) is the product of a "shape function" and a "wave function". The resulting system of equations is

$$\begin{gathered} \sum_{n=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \left\{ \left(L_0 + L_1\right)\bar{\phi} + L_2 \frac{\partial \bar{\phi}}{\partial \bar{x}} + \frac{d\alpha}{d\bar{x}} L_3 \bar{\phi} \right\}_{(n,k)} * \\ A_{(n,k)} e^{i\left(k\beta_0 z - n\omega_0 t\right)} = N \end{gathered} \tag{9}$$

The operators $L_i\,(i = 0,3)$ assume the same meaning as in the LPSE form except that they are applied to each particular mode $\left(\alpha_{(n,k)}, n\omega_0, k\beta_0, \bar{\phi}_{(n,k)}\right)$ where ω_0 and β_0 are the fundamental frequency and spanwise wavenumber, respectively. During the marching procedure, each mode must individually satisfy the normalization condition.

The PSE formulation here utilizes a body-intrinsic coordinate system and the curvature is included in the associated metric coefficients. The marching procedure naturally aligns the disturbance wave propagation in the proper direction. The local radius of curvature of the surface appears in the equations through the following terms:

$$\begin{aligned} k_1 &= 1 + \frac{y}{R_c}, \quad k_2 = \frac{1}{y + R_c}, \\ k_3 &= -\frac{1}{R_c^2} \frac{dR_c}{d\bar{x}} \approx 0, \\ k_4 &= -\frac{y}{R_c^2} \frac{dR_c}{d\bar{x}} \approx 0 \end{aligned} \tag{10}$$

where R_c is the local dimensionless radius of curvature of the surface taken as positive or negative for convex or concave regions, respectively. Curvature is neglected in the basic-state analysis. This is because the basic-state curvature terms are the same order as the terms neglected according to the boundary-layer approximation so it would be inconsistent to retain them. In the limit of infinite curvature (flat plate), $R_c \to \infty$, so $k_1 = 1$ and $k_2 = 0$ are used in the stability equations for cases where curvature is neglected and the above equations are used for cases where curvature is retained.

Haynes and Reed (2000) discretized the PSE using 4th-order-accurate finite differences in the normal direction and up to 2nd-order-accurate backward differences in the streamwise direction.

3. Working with STAR Tool

The TEES/Texas A&M team has advised the Minnesota team on modeling crossflow-instability physics as stationary because of the extreme dependence on leading-edge roughness per the extensive experiments at Arizona State University, as well as provided details of the numerical approach above. At present, the Minnesota team has formulated the STAR tool for 2-D geometries, and has expressed that it will continue to work with the Texas A&M team in the future to fully implement the NPSE for 3-D and general geometries. The Minnesota team is currently using their code for HiFIRE, and they have some encouraging comparisons with tunnel data from CUBRC. As the Minnesota team finishes generating the Fortran code for the 3D problem, they have indicated that they will need the help of the TEES/Texas A&M team as the NPSE comes together.

Many relevant geometries in hypersonic applications are non-conical with spanwise variations in the mean flow. The TEES/Texas A&M team discussed with the Minnesota team the extension of the tool to the study of both crossflow and second-mode instabilities on *general geometries*. To this end, the idea (and challenge) is to identify a marching (parabolic) direction and solve the perpendicular plane with standard finite-difference techniques. The modeling of the disturbances in the marching direction is the challenge, but when we are successful, predictions for non-conical flows will be possible.

- The challenge comes especially for second-mode considerations when the most unstable disturbance wavelengths vary in the spanwise direction but yet streamwise wavelengths are of the same order as the boundary-layer thickness. The appropriate approach is still under discussion.
- When considering crossflow instabilities, the streamwise wavelength of disturbances is relatively large thus still allowing the parabolic approximation even though the most unstable wavelength may vary in the spanwise direction. Thus a crossflow prediction tool for general geometries should be straightforward.

The initial conditions for the NPSE calculation (with curvature) will be formulated as part of the research. For crossflow, initially we will try solutions from local LST models for roughness at the upstream-most chord location. The sensitivity of the transition process to initial amplitude and roughness distribution (Fourier representation) will be evaluated. Saturation amplitudes and secondary instabilities of the distorted profiles will be evaluated.

Reed has traveled to Minnesota to work with Candler and Johnson, and plans to keep visiting when Minnesota indicates that it is time to implement NPSE fully into the STAR tool. In the meantime, Reed has developed in-house capability in NPSE in preparation of providing a verification tool.

4. Transitions

The Texas A&M team is leveraging other Air Force programs, namely RATTraP, MURI, SWIFT, SensorCraft/HiLDA and DARPA QSP, to refine the NPSE methodology in anticipation of its implementation into the STAR tool.

RATTraP. Reed is a member of the Rapid Assessment Tool for Transition Prediction (RATTraP) team with Lockheed Martin in Fort Worth. The Lockheed Martin Aeronautics (LM Aero) team is developing, implementing, and validating a computationally efficient and physically accurate method to predict boundary layer transition on laminar flow swept wings for HALE intelligence, surveillance, and reconnaissance (ISR) aircraft. The LM Aero team has developed a low risk technical approach that will efficiently provide AFRL a transition prediction capability that will enable efficient HALE wing design and optimization. This transition method is also applicable to more general aircraft configurations and flow conditions.

The LM Aero RATTraP program plan was devised to efficiently develop a superior transition prediction method for 3-D wing design and optimization. The LM Aero team is leveraging existing physics-based transition prediction methods through a comprehensive survey. Experimental and theoretical transition results were surveyed and reliable data sets selected for use in validation and calibration of the final transition prediction methodology. The final RATTP software was designed to ensure computational efficiency, effective parallelization and ease of implementation in multiple flow solvers. The RATTraP software was then implemented in two 3-D Navier-Stokes flow solvers, one of which was selected by AFRL. The software is presently being validated using experimental data and stability theory-based methods. The final thoroughly documented products of the RATTP program will be a software design, transition prediction source code modules without any proprietary limitations, an implemented RATTP model in the AFRL code of choice, and a validation database.

SWIFT, SensorCraft/HiLDA. Reed also supports the Flight Research Lab at TEES/Texas A&M generating detailed O-2 flight data for crossflow validation purposes as well as demonstration of Saric's passive laminar flow technique of discrete roughness elements. Reed designed the flight test article through stability analysis, and FLUENT and NPSE results show the feasibility of 2-mm spaced roughness elements to control natural crossflow with a 4-mm wavelength.

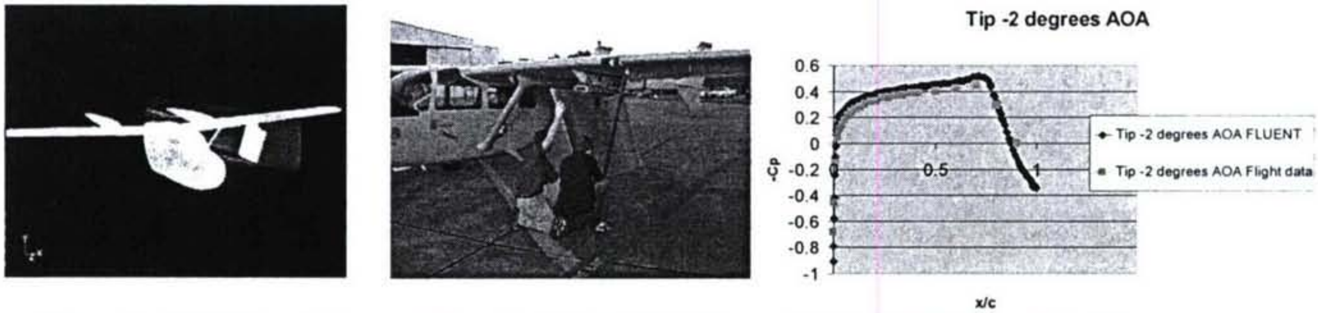

Figure 9. SWIFT model mounted on the O-2 at TEES/Texas A&M, FLUENT model of the flight configuration, and a comparison of flight and computational data showing excellent agreement for –Cp.

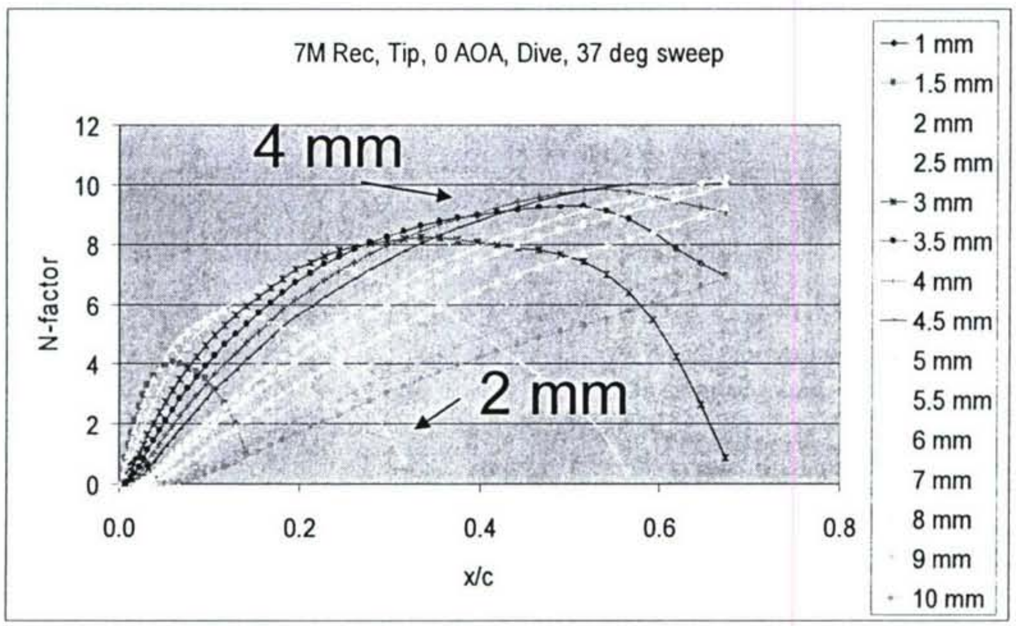

Figure 10. Linear stability theory for the SWIFT model shows crossflow instability wavelength predicted at 4 mm. Discrete roughness elements spaced 2 mm apart at the leading edge will control the crossflow (Saric et al. 1998; Saric & Reed 2002).

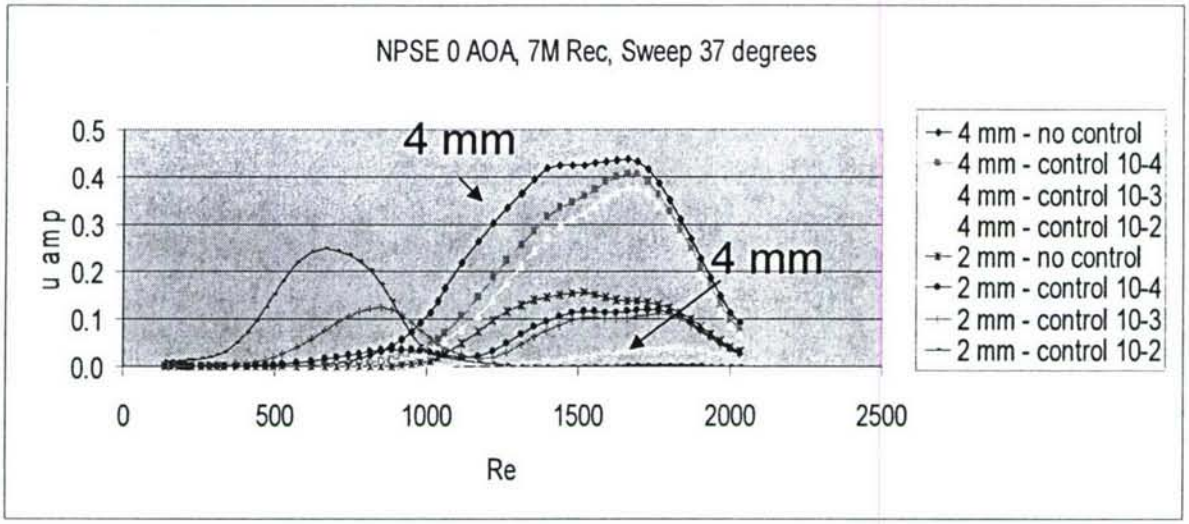

Figure 11. TEES/Texas A&M NPSE predictions show that if control roughness of 2 mm is applied, then 4 mm most dangerous wavelength (dark blue line) will be damped (aqua blue line).

AIAA Professional Development Course. Reed is one of three people who team to offer the AIAA Professional Development Course "Stability and Transition: Theory, Modeling, Experiments, and Applications", first in 2003, then 2006, next in 2008 at Summer AIAA Fluids Meeting. The description of the course is: "Knowledge of transition is critical for accurate force and heating predictions and effective control (both transition delay and enhancement). This course is intended to present a comprehensive and critical review of current methods used to determine the physics, onset, and extent of transition for a wide variety of 2D and 3D flows, both high- and low-speed. Tools reviewed will include the e^N method based on linear stability theory (LST), Parabolized Stability Equations (PSE), and Direct Numerical Simulations (DNS). Guidelines for experiments and flight tests are reviewed. Then, a comprehensive review of transition region models will be provided to include algebraic/integral and differential models. In particular, an approach, in which one calculates the onset and extent of transition as part of the solution at a cost typical of turbulent flow calculations, will be presented. Once the user specifies the transition mechanism, the eddy viscosity of the non-turbulent fluctuations is provided." Reed is responsible for teaching:

- o Review of the roadmap to transition, including receptivity, attachment line, transient growth, stability, and breakdown
- o Current tools – Linear Stability Theory, Parabolized Stability Equations, Direct Numerical Simulations
- o Verification and validation for various 2D and 3D flows

Reed has also taught these topics at AFRL in Dayton and Lockheed Martin in Fort Worth.

AFOSR MURI. Reed is a member of the AFOSR MURI team researching "Hypersonic Transition and Turbulence with Non-Equilibrium Thermo-Chemistry" with Sharath Girimaji and Rodney Bowersox. She is participating in the tasks related to

- o Free shear-layer experiments and model development, and the investigation of hypersonic transition in free-shear layers.

- o CFD integration, testing and validation, which includes integration of numerical procedures, transition calculation and turbulence models.

She is using a combination of LST and NPSE Bowersox' shock-induced shear layer (SISL) experiments to

- o Determine relevant physics of transition for shear layers with non-equilibrium thermo-chemistry
- o Develop models for predicting transition onset and extent to incorporate into our CFD capability to initiate turbulence models (precise upstream length and velocity scales)

Graduate Student. Masters student Richard Rhodes, U.S. Citizen, has learned about stability and transition, LST, NPSE, and verification and validation, and he is expected to graduate in May 2008. He intends to continue working in this field.

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EDUCATION

Ph.D.	Engineering Mechanics	Virginia Tech	Dec 1981
M.S.	Engineering Mechanics	Virginia Tech	June 1980
A.B.	Mathematics	Goucher College	May 1977

EXPERIENCE

Dec. 2004-present	Texas A&M, Professor and Head, Aerospace Engineering
Aug. 1985-present	Arizona State University (ASU)
Jan. 2005-present	Emeritus Professor, Mechanical and Aerospace (MAE)
July 2003-Aug. 2004	Vice Chair for Graduate Programs, MAE
July 1992-Dec. 2004	Professor, MAE
Dec. 1994-Dec. 2004	Associate Director, ASU / NASA Space Grant Program
Aug. 1993-Aug. 1996	Director, Aerospace Research Center
Aug. 1985-June 1992	Associate Professor, MAE
Sept. 1991-June 1992	Tohoku Univ., Sendai, Japan, Associate Professor
Sept. 1982-Aug. 1985	Stanford, Assistant Professor, Mechanical Engineering
June 1977-Dec. 1981	NASA/Langley Research Center, Aerospace Technologist

PROFESSIONAL ACTIVITIES

Awards and Recognitions

Fellow, American Physical Society (APS), September 2003
Fellow, American Society of Mechanical Engineers (ASME), July 1997
AIAA/ASEE J. Leland "Lee" Atwood Award, bestowed annually upon an aerospace engineering educator in recognition of outstanding contributions to the profession, 2007
Excellence in Service Award, Faculty Achievement Award, ASU Alumni, Founders' Day, March 12, 2003.

Other Scientific and Professional Societies

Associate Fellow, American Institute of Aeronautics and Astronautics (AIAA)
Member, AMSAT (Radio Amateur Satellite Corporation)
Member, American Society for Engineering Education (ASEE)

Service to the Profession

Served on various NASA Headquarters Aeronautics Advisory Committees, Subcommittees, Task Forces; NASA Federal Laboratory Review Task Force of NASA Advisory Council; and NATO/AGARD Fluid Dynamics Panel. Presently

- Chair of the Aerospace Department Chairs' Association
- Member, U.S. National Transition Study Group under direction of Eli Reshotko
- Science Advisory Board for National Institute of Aerospace (NIA)

- Texas A&M Institutional Representative for USRA
- Instructor, AIAA Professional Development Course on "Stability and Transition: Theory, Modeling Experiments, and Applications," with Drs. Hassan Hassan and William Saric

Current Fields of Interest

Boundary-layer transition and flow control, hypersonic flow, micro-/nano-satellite design, responsive systems – software and hardware architectures, autonomous rendezvous and docking, unmanned and micro aerial vehicles, integrated concurrent engineering and systems design. Recent work includes:

- Design swept wings using Saric-developed discrete-periodic-roughness laminar-flow technology. Validate crossflow instability data with Nonlinear Parabolized Stability Equations.
  - DARPA Quiet Supersonic Platform on F-15B at NASA-Dryden, wind-tunnel tests at NASA-Langley
  - Air Force HiLDA/Sensorcraft program and flight tests at Texas A&M
  - Collaborate with Lockheed Martin and Northrop Grumman
- Rapid analysis tools for transition prediction (RATTraP with Lockheed Martin) – Develop, implement, and validate a computationally efficient and physically accurate method to predict boundary layer transition on laminar swept wings for high-altitude long-endurance (HALE) intelligence, surveillance, and reconnaissance (ISR) aircraft. Provide AFRL a transition prediction capability that will enable wing design and optimization.
- Stability and transition of hypersonic chemically reacting boundary layers on reentry vehicles
- Aerodynamic control of micro aerial vehicles
- Plug-and-play and multifunctional micro aerial vehicle technologies

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